Operating CM-1, an 8-cavity TESLA-Style Cryomodule

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All Experimenters Meeting

27 June 2011

Outline

- CM-1 Introduction
- Milestones
- Test Plan
- Results
- Future Plans
- Conclusion

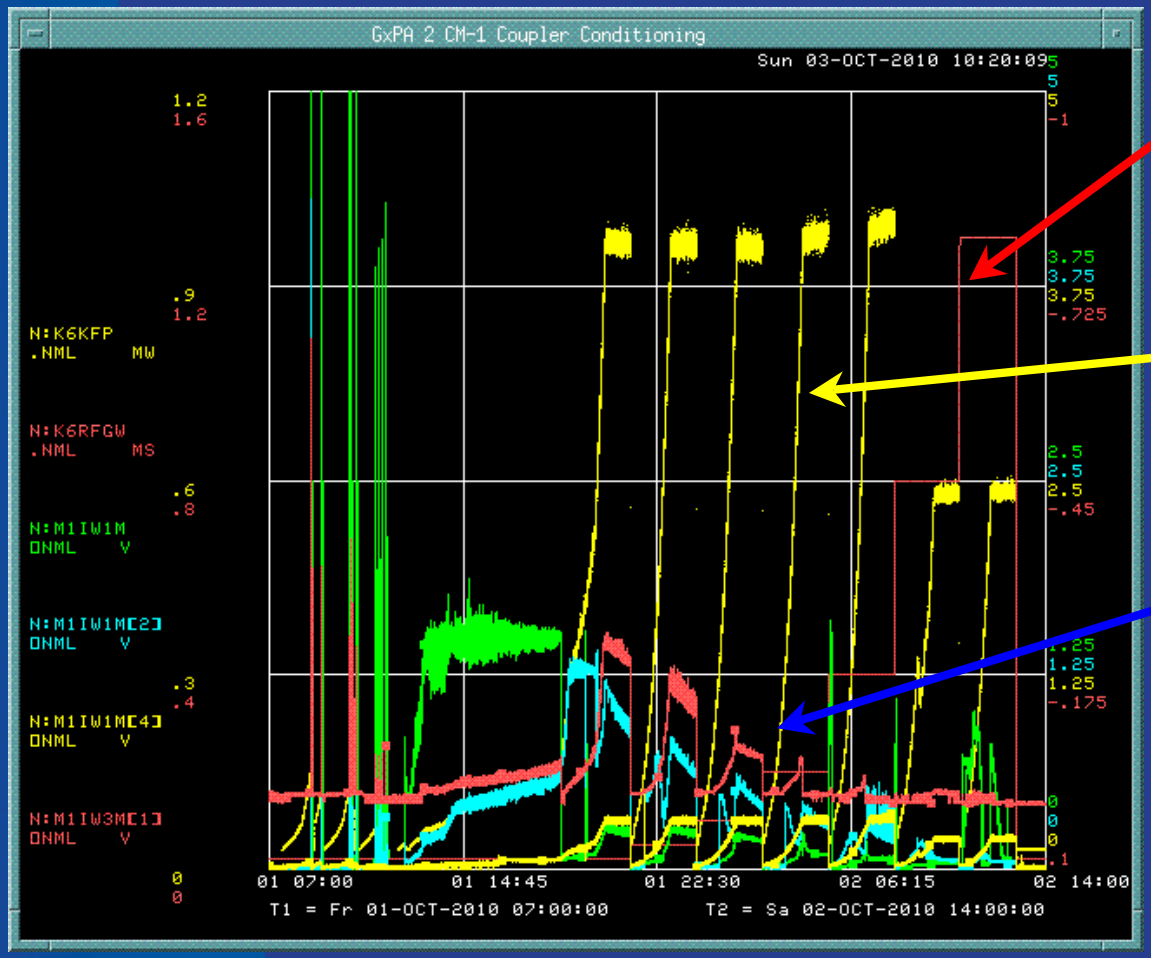
Introduction / What is CM1?

- Cryomodule 1, also dubbed ‘S-1 Local’
- TTF Type III+ 8-cavity cryomodule
  - First one in the U.S.
- Provided to Fermilab by DESY as a ‘kit’
  - Assembly by Fermilab, DESY, INFN-Milano
  - In exchange for 3.9 GHz cryomodule
    - Now in routine operation at DESY/FLASH
- Assembly at Fermilab
- Now installed at the refurbished New Muon Lab experimental hall

Milestones

- Significant Progress has been made towards making CM1 operational in the past 18 months
  - 22 January 2010: Cryomodule moved into final position and aligned
  - 23 February 2010: Warm side of input couplers under vacuum
  - March - May: Cryogenic piping connections
  - 11 June 2010: permission to initiate RF commissioning and warm coupler conditioning
  - June - July: RF/Klystron commissioning
  - 2 August 2010: Warm coupler conditioning begins, one cavity at a time, beginning with Cavity 8/S33
  - 16 August 2010: Cavity 8 conditioning complete (14 days)
  - 26 August 2010: Cavity 7/Z91 conditioning complete (10 days)
  - 2 September 2010: Cavity 6/Z98 conditioning complete (8 days)
  - 17 September 2010: Cavity 5/Z107 conditioning complete (15 days)
  - 22 September 2010: Cavity 4/Z106 conditioning complete (6 days)
  - 27 September 2010: Cavity 3/AC73 conditioning complete (6 days)
  - 30 September 2010: Cavity 2/AC75 conditioning complete (4 days)
  - 3 October 2010: Cavity 1/Z89 conditioning complete (4 days)

Warm Coupler Conditioning



Pulse Width
(20 μs - 1.2 ms)

Input power
(up to 1 MW)

Field Emission
probe and PMT
Response
(0-5 volts)

Cavity #1 (Z89)

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Milestones (2)

- 12 November 2010: Insulating vacuum space leak tight and pumped down
- 23 February 2010: Warm side of Couplers under vacuum
- 17 November 2010: Cool down begins
- 19 November 2010: Cool down to 4.5 Kelvin complete
- 22 November 2010: At 2 Kelvin
- 10 December 2010: Permission to initiate cold RF operation
- 13 December 2010: Cold coupler conditioning and Performance evaluation begins, one cavity at a time, first RF into CM-1 at Fermilab
- beginning with #1
- 17 December 2010 - 26 January 2011: Cavity 1/Z89
- 28 January 2011 - 7 March 2011: Cavity 8/S33
- 7 - 16 March 2011: Cavity 2/AC75
- 18 - 22 March 2011: Cavity 1/Z89 *reprise*
- 26 March - 4 April 2011: Cavity 3/AC73
- 20 April - 19 May 2011: Cavity 4/Z106
- 20 - 25 May: Cavity 5/Z107
- 3 - 9 June: Cavity 6/Z98
- 9 - 11 June: Cavity 7/Z91

Performance Evaluation Steps

- Each cavity is singly connected to the output of the klystron to determine its performance.
- A prescribed series of measurements are made following the 'DESY recipe' test sequence at the Cryo Module Test Bench (CMTB)
  - RF Cable Calibration
  - Technical Sensor/Interlock Check
  - RF/Waveguide Check
  - Warm Coupler Conditioning (off resonance)
  - Cooldown to 2K
  - Frequency spectra measurements
  - Cavity Tuning to 1.300 GHz via motorized slow tuner
  - Q_L adjust to 3 E6
  - LLRF calibrations
  - Cold Coupler Conditioning (on resonance)
  - Performance Evaluation including
    - Maximum gradient
    - Dynamic Heat Load (Q_0 vs. E_{ACC})
    - Dark Current and X-rays vs. E_{ACC}
- Once pairs of cavities are tested, they will be connected to the waveguide distribution system.
- Ultimately all 8 cavities will be powered simultaneously by the 5 MW Klystron.

Evaluation Summary

- Cavity #1 (Z89) assessment complete
  - 18 MV/m, high heat load
- Cavity #8 (S33) assessment complete
  - 23.5 MV/m, tuner motor shorted
- Cavity #2 (AC75) assessment complete
  - 27.5 MV/m, ok
- Cavity #3 (AC73) assessment complete
  - 16.5 MV/m, high heat load
- Cavity #4 (Z106) assessment complete
  - 28.1 MV/m, ok
- Cavity #5 (Z107) assessment complete
  - 33.8 MV/m, ok
- Cavity #6/Z98 assessment complete
  - 28.1 MV/m, ok
- Cavity #7/Z91 assessment complete
  - 22 Mv/m, marginally high heat load, ok
- *All cavities have now been individually evaluated*

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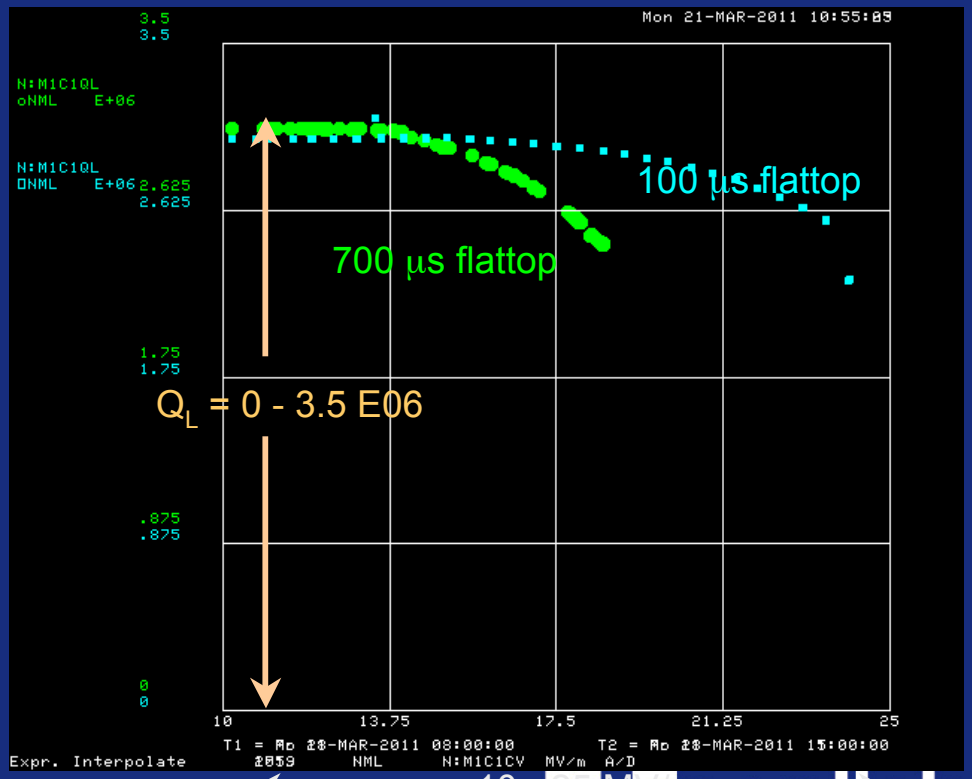
Cavity 1/Z89 Performance

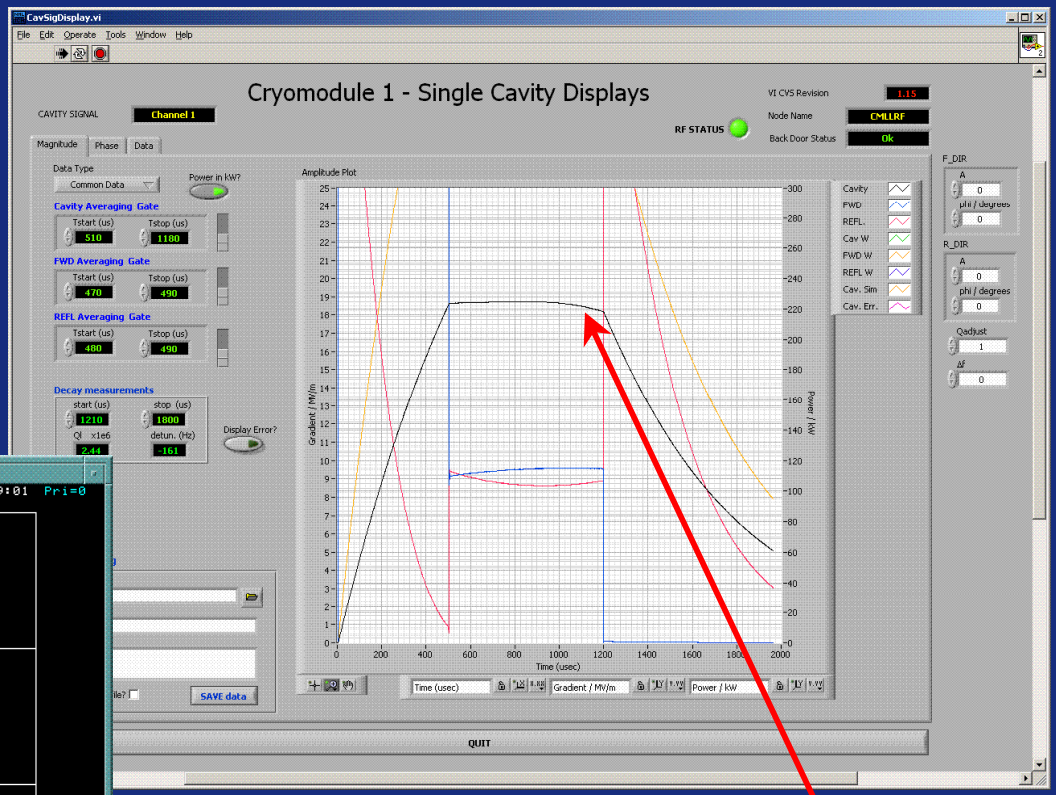
- Determination of Cavity gradient limit: *23-24 MV/m*, consistent with Chechia tests (maximum 2 HZ repetition rate, 1.2 ms pulse length)
- Stable operation at 18 MV/m
- Cryo Heat Load larger than expected
- Large Q drop vs. gradient
- Insignificant Dark Current and X-rays

Variation of Q_L with gradient



Cavity 1/Z89 Performance

- Cavity 1/Z89 re-testing
  - Previous results, especially larger than expected heat load reproducible? Yes
  - Dynamic Heat Load characterization



Quench?

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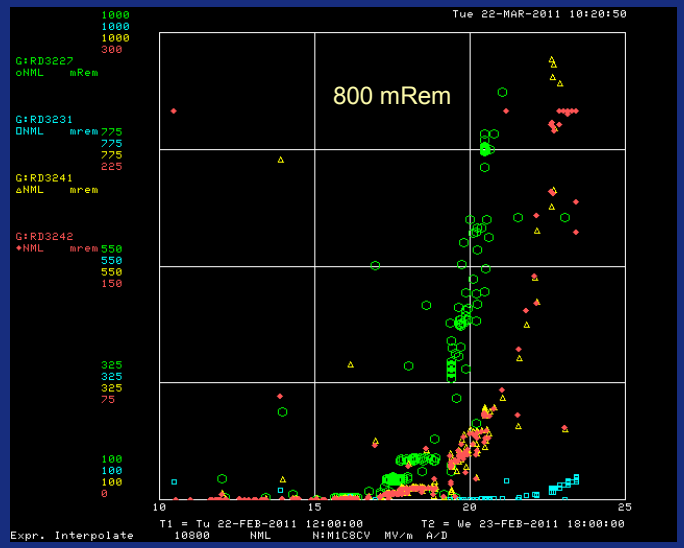
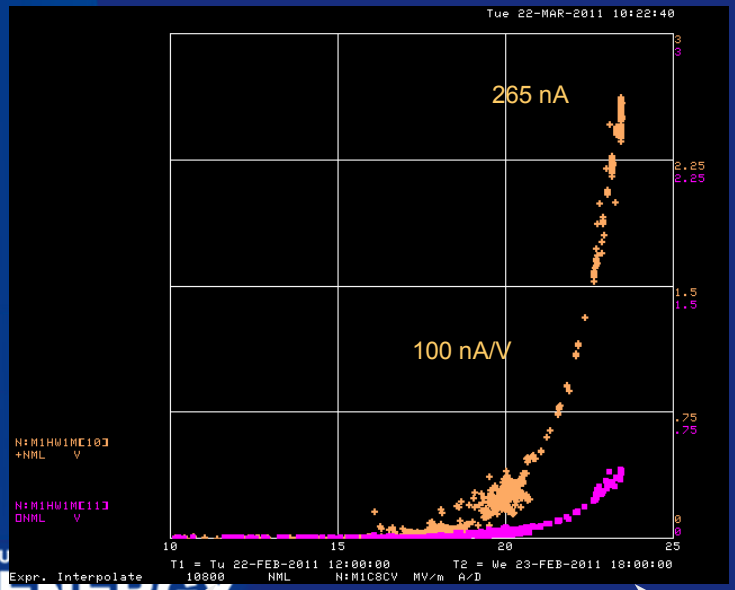
Cavity 8/S33 Performance

- Tuner Motor freezes after ~119/361 kHz motion, motor appears to be shorted
- LLRF master oscillator tuned to cavity frequency, 1.300 241 800 GHz
- Peak Gradient - 23.5 MV/m, quench limited (5 Hz repetition rate, 1.2 ms pulse)
- Q_0 ~ 1.5 E10
- Dark current and X-rays detected



10 - 25 MV/m

Maximum X-rays at opposite end of Cryomodule



10 - 25 MV/m

Maximum Dark Current at opposite end of Cryomodule

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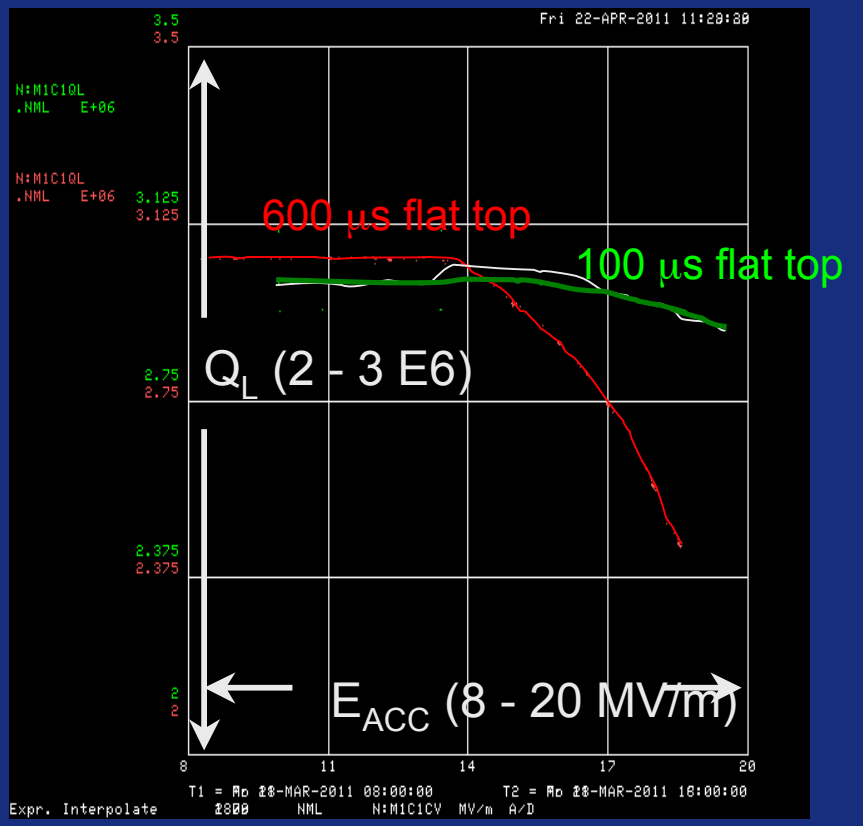
Cavity 3/AC73 Performance

- Uneventful Coupler Conditioning
- Tuner operation fine (no motor problems)
- Maximum gradient achieved - 19 MV/m
  - Limited to 2 Hz
  - Significant cryogenic response
  - No X-rays or Dark current detected
  - No clear quench indication
- LLRF closed loop operation
- LFDC demonstrated



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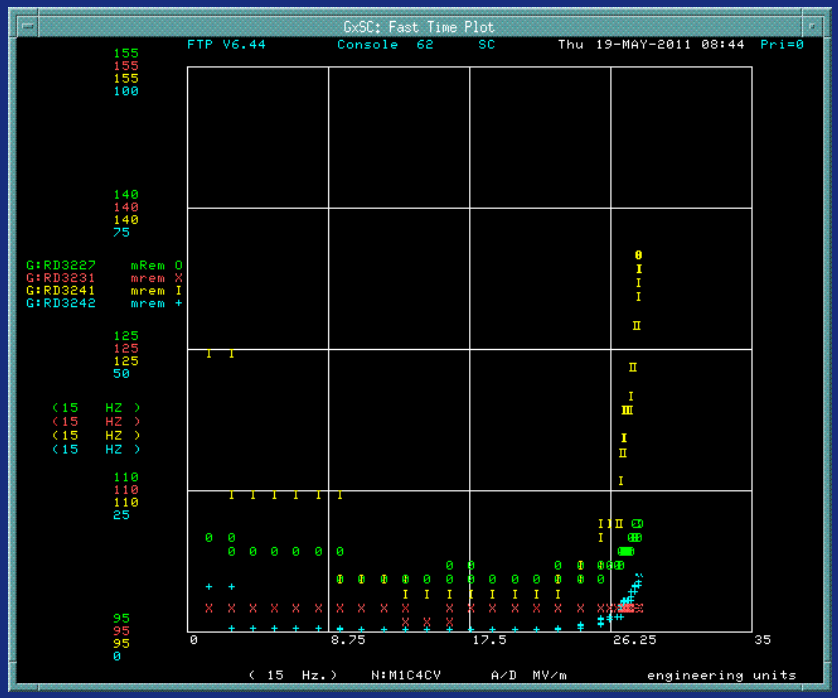
Cavity 4/Z106 Performance

- Coupler Conditioning took quite a while
  - 200 μs, up to 1MW sequence
- Tuner operation fine (no motor problems)
- Maximum gradient achieved - 28.1 MV/m
  - 5 Hz
  - Abrupt quenching
  - X-rays detectible only during higher gradient operation - at middle of cryomodule
- LLRF closed loop operation
- LFDC demonstrated



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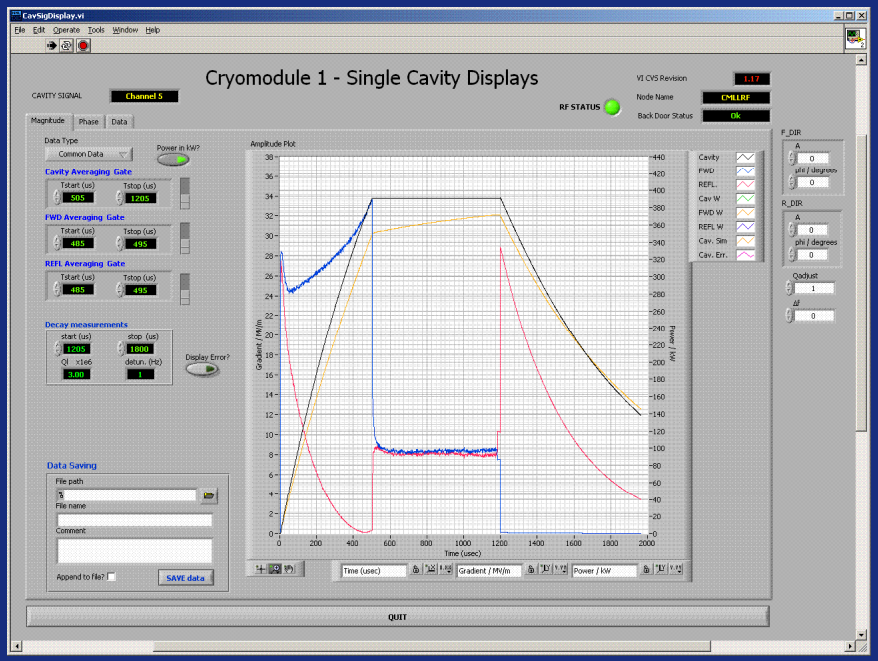
Cavity 5/Z107 Performance

- Very quick Coupler Conditioning (24 hours)
- Tuner operation fine (no motor problems)
- No anomalous behavior seen (cryo is stable to quench limit)
- Some x-rays
- Peak performance
  - 33.8 MV/m, quench limited
  - LLRF closed loop set up
  - LFDC tuned up
  - Limited to 2.5 Hz operation with 1.2 ms pulse width by LCW temperature, flow



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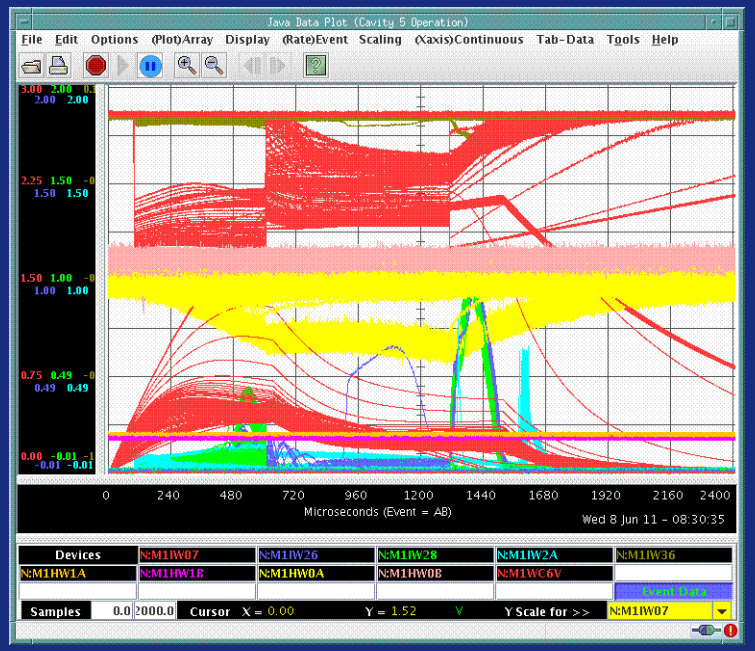
Cavity 6/Z98 Performance

- Rapid Coupler Conditioning (3 days)
- Tuner operation fine (no motor problems)
- No anomalous behavior seen (cryo is stable to quench limit)
- No x-rays
- Peak performance
  - 28.1 MV/m, quench limited
  - LLRF closed loop set up
  - LFDC tuned up
  - 5 Hz operation with 1.2 ms pulse width



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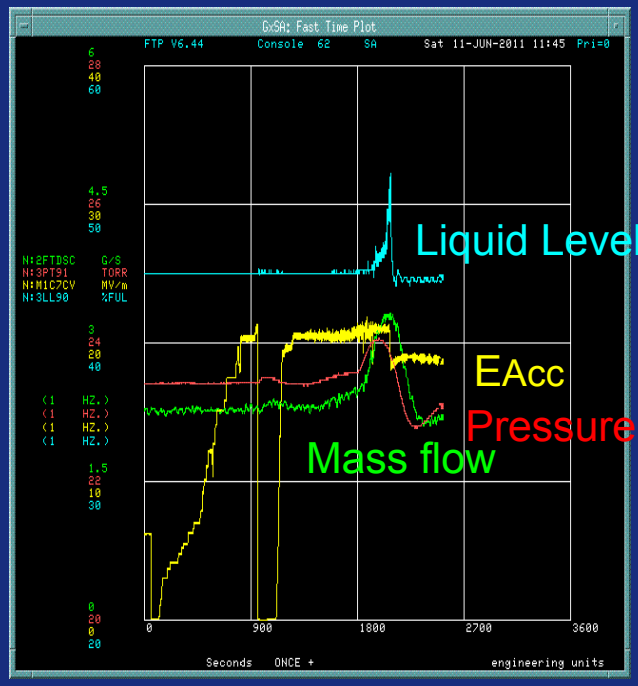
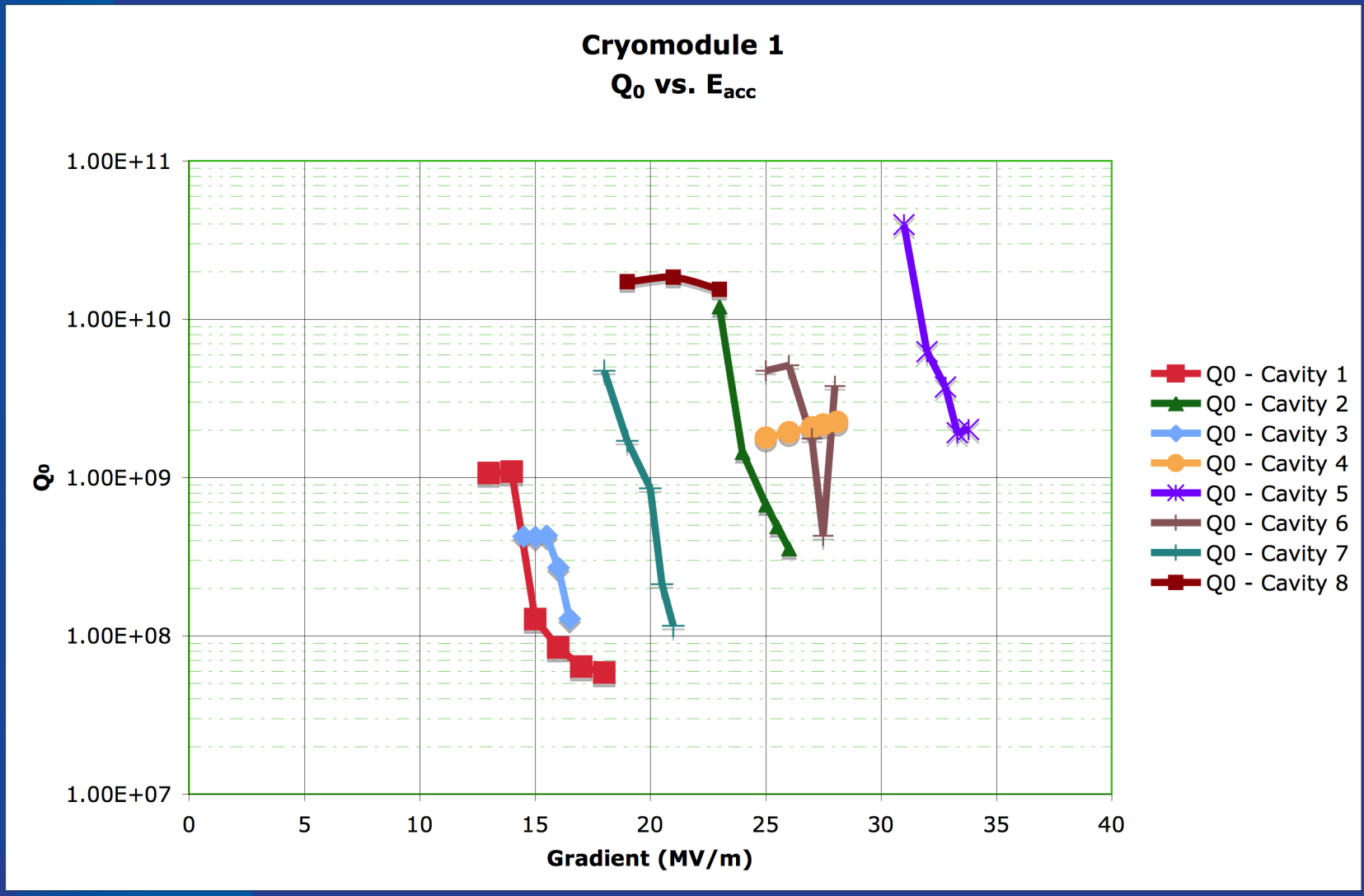
Cavity 7/Z91 Performance

- Quick Turnaround and rapid Coupler Conditioning (2 days)
- Tuner operation fine (no motor problems)
- Cryo instabilities just above 21 MV/m, but prior to quenching
- Q_L drop with gradient
- No x-rays
- Peak performance
  - 22 MV/m, cryo and quench limited
  - LLRF closed loop set up
  - LFDC tuned up
  - 5 Hz operation with 1.2 ms pulse width



Cryo Response ~ 20 MV/m

Q_0 vs E



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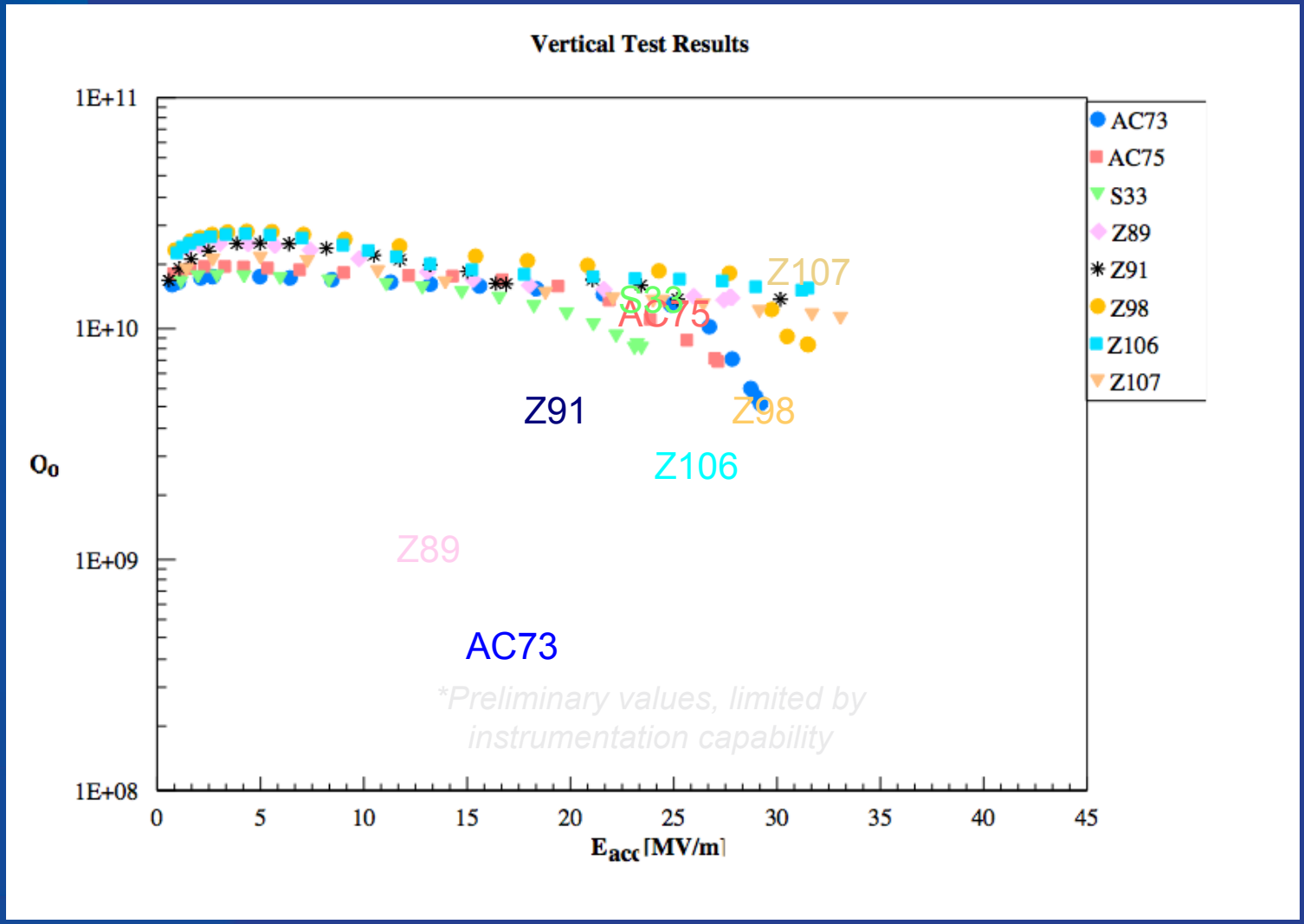
Q vs E Compared to DESY Data



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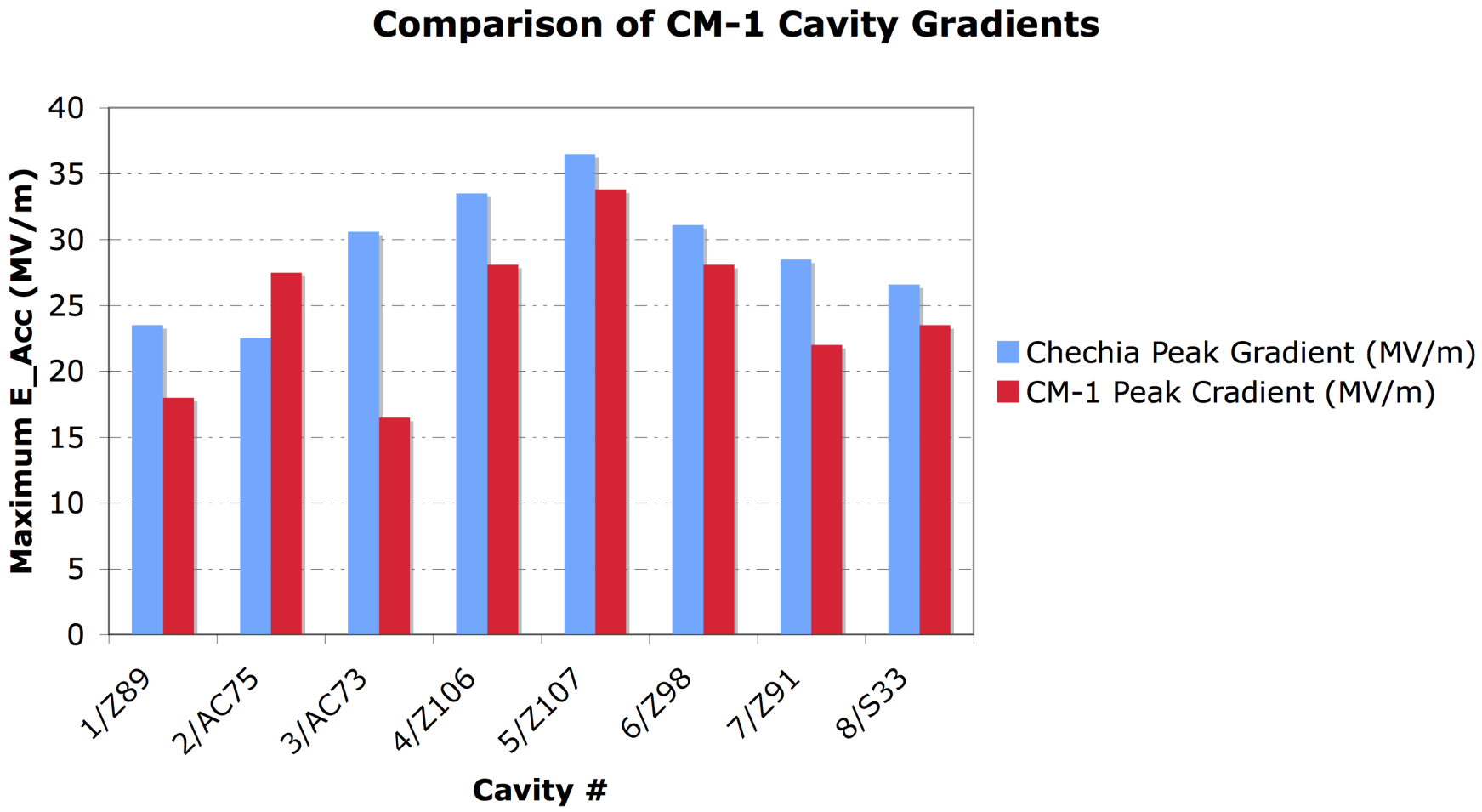
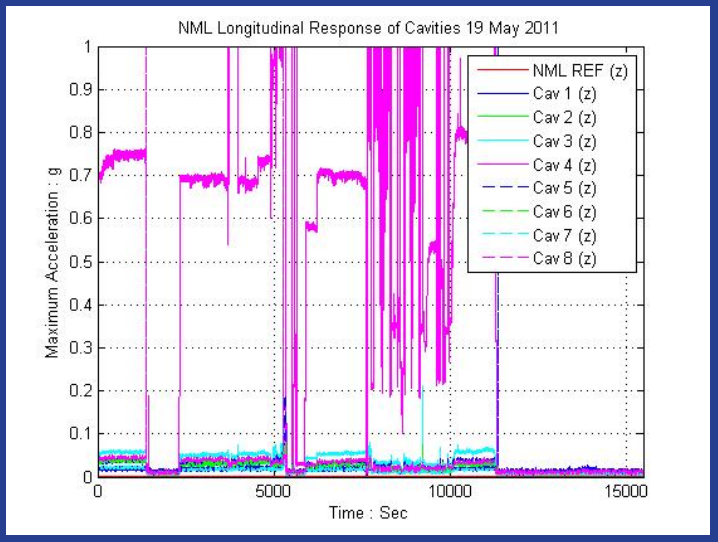
CM-1 Comparative Gradients

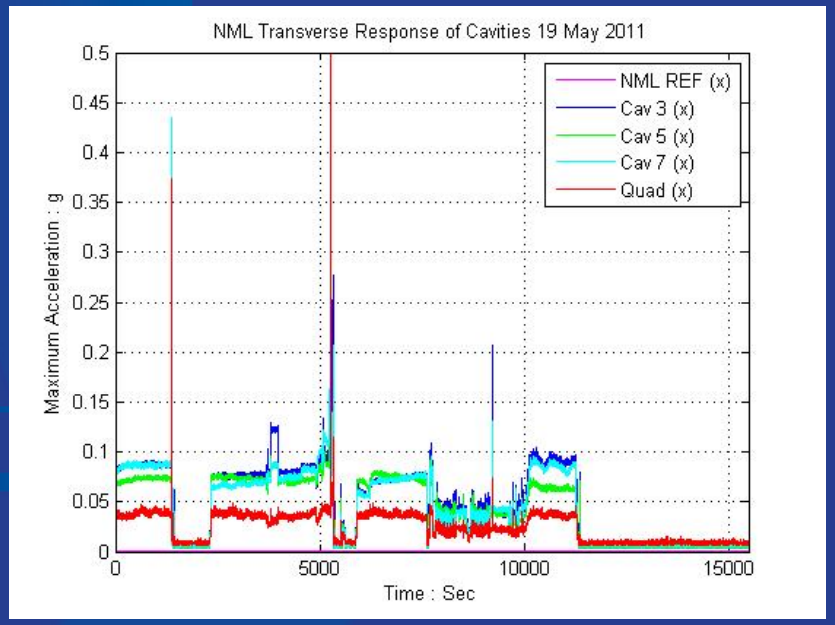


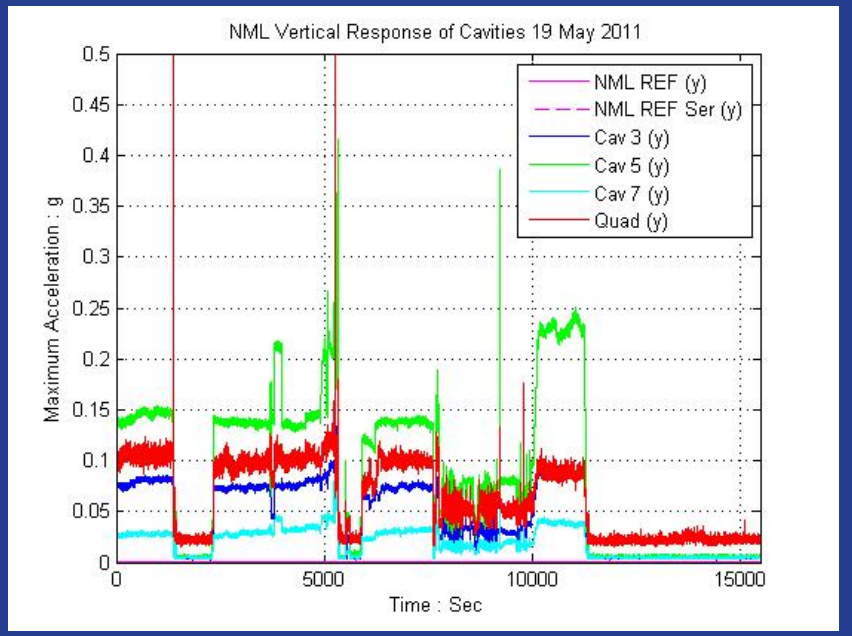
Subsystem Performance - Microphonics

- System evolving
- Interfaced to ACNET
- Ongoing improvements



Cavity 4 Operation





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Next

- Follow-up testing on selected cavities
  - More DHL on cavity 7
- Begin Module testing thereafter

Module Test Plan

1) Signal calibrations verified (1/2 day) 0.5
2) Waveguide distribution system assembled to all cavities (2 weeks) 10.0
3) Adjust Variable Tap Off's (VTO's) based on cavity maximum gradient data (2 days) 2.0
4) Adjust phase shifters – minimize field emission, dark current?
5) Verify power to cavities as seen on directional couplers (1/2 day) 0.5
6) Set Q_L = 3 E6 for all cavities (1/2 day)
   a. LLRF system should be ready for real time Q_L measurements 0.5
7) Set cavities to as close to the same resonant frequency as possible (except #8) (1/2 day) 0.5
   a. LLRF should be ready for real time df measurements
8) Determine maximum achievable E_{ACC} (1 day) 1.0
9) Verify system LFDC/piezo system (6 months/3 weeks) 15 (parasitic)
10) Investigate Microphonics (parasitic)

Module Test Plan - 2

11) Determine LLRF regulation limits (3 days) 3
    a. Assess any potential issue with 8/9 pi modes (7-8 of them)
    b. Adjustable gain in LLRF controller to control 7 or 8 cavities
    c. FF operation
    d. Test phase and amplitude calibration scheme
    e. FB operation
    f. Test real time measurements (Ql, detuning, control error, system noise)
    g. Evaluate controller performance and regulation limits
12) Measure dark current/x-rays levels and source(s) (mostly parasitic)
13) HOM signal investigation (mostly parasitic)
14) Investigate possible cross-talk between cavities: de-tune one cavity at a time to investigate response (2 days)
    2
15) Cryo heat load (should be parasitic)
16) Life test – investigate stability over 100? Hours 5
    a. Stability / drift analysis (requires waveform DAQ storage system)
17) 9mA related studies (Carwardine et al, meeting next week) (tbd)
    5
18) higher Q (1E7) /P-X studies resonance control 3

*48 days/5 = 9+ weeks

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Not Just Cavity Testing

- Although the priority, CM-1 operation has competition for time:
  - NML is still a construction area
    - Tunnel extension
    - Electrical Upgrades
    - Water system
  - Gun window evaluation and conditioning (typically 1-2 days/week)
  - Photoinjector installation
  - Tours
  - Performance limitations
    - Insufficient LCW capacity and cooling
    - New skid coming on-line now
- Strive to run as much as possible
  - Overnights and weekends when practical and testing program allows
  - Growing involvement by MCR crews

Summary

- Cold operation of CM-1 in progress since November 2010
- Single cavity performance measurements are completed
  - 8 cavities; mixed results
- All sub-systems being understood and characterized
- Successes
  - Stable Cryogenics system
  - Evolving and flexible Controls
  - Growing involvement by AD/Operations
- A few issues
  - Tuner motor - Cavity 8
  - Cavities 1, 3, 7 Heat Load: other things to look at
- Move on to Module testing in very near future

the Team

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